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MEASURED WATER TEMPERATURE CHARACTERISTICS IN A PIPELINE DISTRIBUTION SYSTEM

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ABSTRACT

This paper describes the design, development, deployment and performance assessment of a prototype system for monitoring the "health" of a water distribution network based on the temperature distribution and time-dependent variations in temperature across the network. It has been found that the water temperature can reveal unusual events in a water distribution network, indicated by dynamic variations in spatial temperature differential. Based on this indication it is shown how patterns of changes in the water temperature can be analysed using AQUIS pipeline distribution software and used in conjunction with hydraulic (e.g. flow and pressure) sensors to indicate the state of "health" of the network during operation.

KEYWORDS

Asset management; detection; distribution; leakage; networks; pipes; sensors; temperature; water.

INTRODUCTION

Leakage in water distribution systems can have serious negative economic, environmental and political consequences. Although water is apparently freely available thanks to God, water supplies are not always predictable and shortages can occur. A significant amount of water can be lost in the distribution networks; up to 30% in older systems (Bridges and MacDonald, 1991). Unaccounted-for-water (UFW) is the term used by the water industry to represent the difference between net production and consumption, and the largest component of UFW within a distribution system is leakage (Braam *et al*., 1997).

The initial challenge in leakage management is to identify the existence of water loss. Often this can be visible evidence, such as surface water, which also helps to locate the leak. However, the monitoring of zones within water distribution networks, which is becoming increasingly implemented, open up potential for the identification of unusual patterns of behaviour.

Monitoring usually makes use of sensors that measure hydraulic characteristics of the water flow (for example flow and pressure) at points within the distribution network. District flow metering is based upon the subdivision of the distribution system into discrete district meter areas (DMAs) using valves. The flows into and out of each zone are then measured at appropriate entry / exit locations.

Although the monitoring of hydraulic parameters such as flow and pressure provides important and valuable data, the high cost of the sensors means that they are not deployed in sufficient density to provide, in themselves, sufficient information about unusual patterns of behaviour. Data from hydraulic sensors located at the entry to and exit from a DMA, needs associated local knowledge and expertise, to provide an estimate of an unusual event. Then accurate location can only be achieved by careful analysis of the signals in conjunction with some state predictive system.

Water companies also use other sensors, typically for assessing water quality, and these may include temperature, turbidity, conductivity, pH, dissolved oxygen. Each one of these variables can also provide information for event detection - in particular the water temperature, which is the subject of this paper (Marshall 99). There is (Skipworth *et al.*, 1999) a complex relationship between air temperature, ground temperature and water temperature. Precipitation and air temperature influence soil moisture content and ground temperature and, in turn, ground movement. Extreme weather conditions resulting in unusual ground movements and / or demand conditions can cause an increase in leak or burst rates. Air temperature also influences water temperature. Lackington (1991) refers to work which showed that when air temperature falls below ground temperature, the burst frequency increases as much as five times, due to soil movement and the subsequent additional superimposed loads. Ground movement and the temperature gradients set up across pipes due to changes in, for example, water temperature have been shown to be driven by meteorological variations which take place over periods of weeks or months (Habibian, 1994).

This paper investigates these questions, using the simple low-cost measurement of temperature. Sensors have been designed and manufactured which provides a low grade time series signal data in a spatial array which may then be analysed by the use of pattern recognition methods.

Results from simulated "burst trials" are also presented which serve to validate the sensor performance and investigate the reaction of water temperature in the network to definite events e.g. flushing. The paper concludes that a low-cost temperature sensor is a practical way of providing data for event detection which is complementary to existing hydraulic measurements.

SENSOR DESIGN AND DEVELOPMENT

Prototype sensor design

The working principle of the temperature sensor was defined as, "the temperature of the soil surrounding a pipe with a leak or burst should be close to that of the water inside the pipe while water from inside the pipe continues to leak into the soil". A differential temperature sensor was therefore designed to measure the difference between the water temperature inside the pipe and the ground temperature adjacent to the pipe (ideally about 1m away).

The sensor identifies a local event and hence for full-scale monitoring of the distribution system, a large number of sensors would need to be installed in the network. This is not practical due to the large numbers of installations and the associated cost, however the sensor can be used for event identification by comparing the reading at one or more sensor locations with the reading obtained from the sensor nearest to the reservoir sensor. This is the technique used in the work presented here.

The designed selected was essentially a thermocouple with an established temperature-output relationship so no further calibration work was needed. The calibration for the sensor was determined from tables of thermoelectric voltage against temperature for the Type-T (copper/constantan) thermocouple. However the functionality of the sensor was checked by varying the temperature of one junction while the other junction probe was immersed in a large vessel of water maintained at a steady temperature. Although thermocouples are not linear, calibration curves of temperature difference vs. output derived from tables of thermoelectric voltages showed that there was sufficient accuracy over the expected temperature range (Khan *et al*., 2002).

A printed circuit board (PCB) was designed and assembled for the differential temperature signal conditioning. The circuit was functionally tested under laboratory conditions using the differential temperature calibration equipment.

Data- logging

A dual channel data logger (Lascar Electronics Ltd., EL-3-12bit) having a storage capacity of 8000 readings per channel in its on-board memory was selected. The logger was located in a weatherproof enclosure along with a ±8V regulated DC power unit for the sensor and signal conditioning. A small thermostatically controlled heater was installed inside the enclosure to ensure that the data logger was maintained within its specified operating temperature range and to minimise the risk of condensation.

Data was manually downloaded to a laptop computer at the sensor location. The data logger was configured to sample at 5 minute intervals, providing up to 25 days data storage capacity at the sensor location.

Sensor installation

A specially designed casing, fitted with the sensor and fully sealed, was installed into the pipe via a special 'T' housing made over the main pipeline at the selected location. A concrete underground enclosure through which the pipe passed was initially used for convenience, but the hot junction probe of the differential temperature sensor could only be buried in a thin layer of soil inside the enclosure. The first prototype of the differential temperature sensor was tested and found to withstand the high pressure within the water distribution system.

EXPERIMENTAL INVESTIGATIONS

Two "burst trials" were organised to check the behaviour, integrity and performance of the sensors (Figure 1). The maximum flow rates that were permissible at each site for the experiments were specified. These were set so that there should be no risk of damage to any of the pipelines and minimising any disturbance.

4 experiments were performed on consecutive nights so that features in the measured response could be identified with any particular event. In order that the phase difference between temperature changes at the ten sensors could be measured, the logging interval at each sensor was changed from 5 minutes to 1 minute and the loggers were carefully synchronised.

The experiments simulated a "burst" by opening a fire hydrant. A standpipe was fitted to the selected hydrant which was then slowly opened to prevent unnecessary disturbance to the water flow. An in-line flow meter was connected and the hydrant was opened until the desired flow rate was reached. Once the required flow rate was achieved the flow meter was removed.

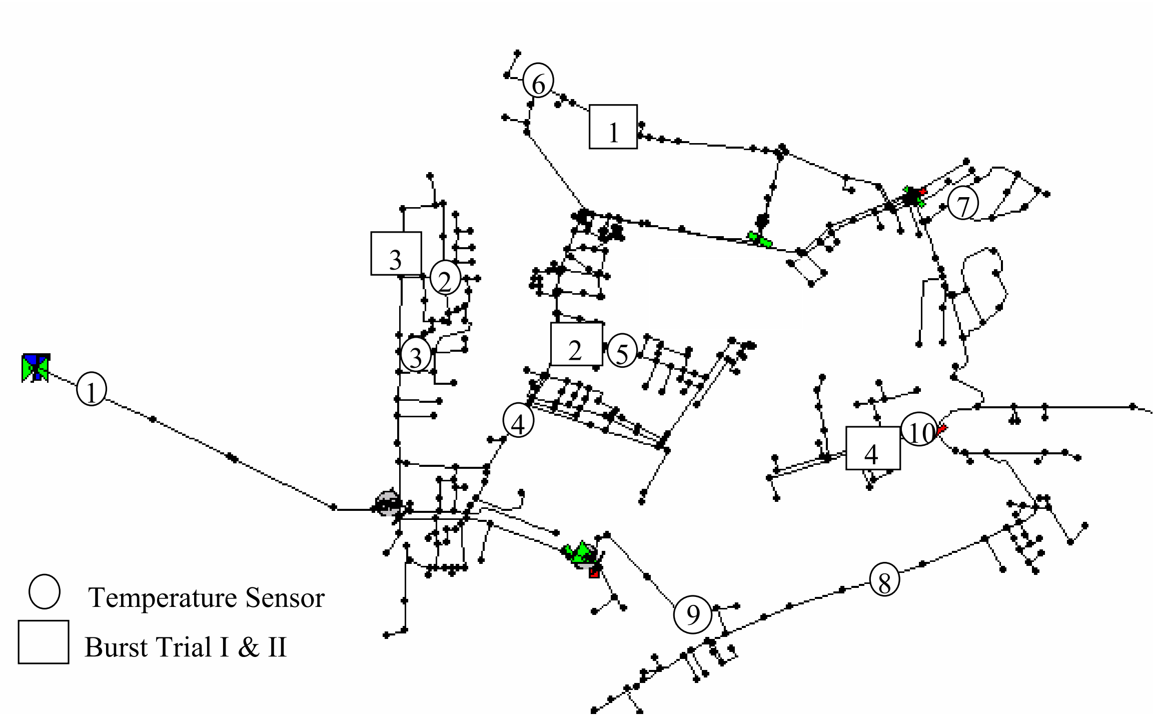

Figure 1: Temperature sensor locations and simulated burst sites in the DMA

Throughout each experiment the water temperature at sensor locations 2-10 was monitored and recorded on a data logger at each sensor site. The water temperature data recorded during Trial I is shown along with the flow rates and timings for each experiment in Figure 2. The temperature data for the sensors is shown more clearly in Figures 3—5 which are plotted at larger scales. After normalisation, a reduction in reading for the duration of the burst at nearby sensors can be seen. This reduction is caused by drawing the reservoir temperature (which is about 3°C less than the network water temperature) into the pipeline concerned.

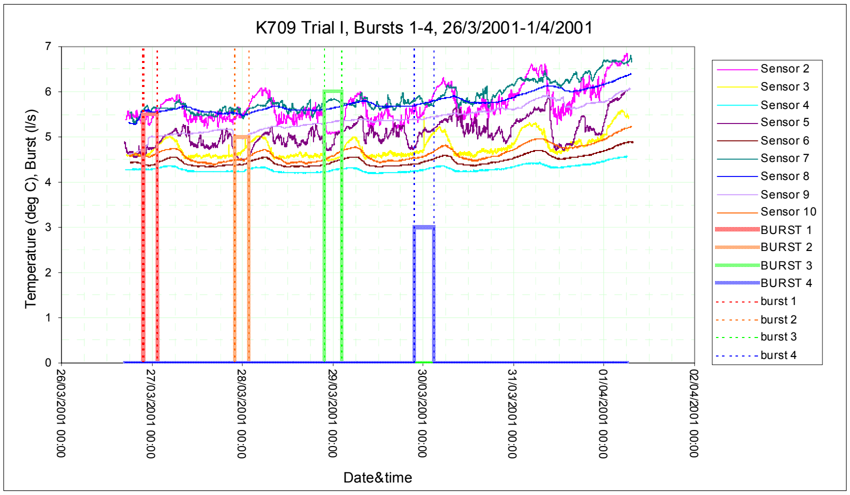

Figure 2: Recorded Temperature Data for Burst Trial I – All Bursts

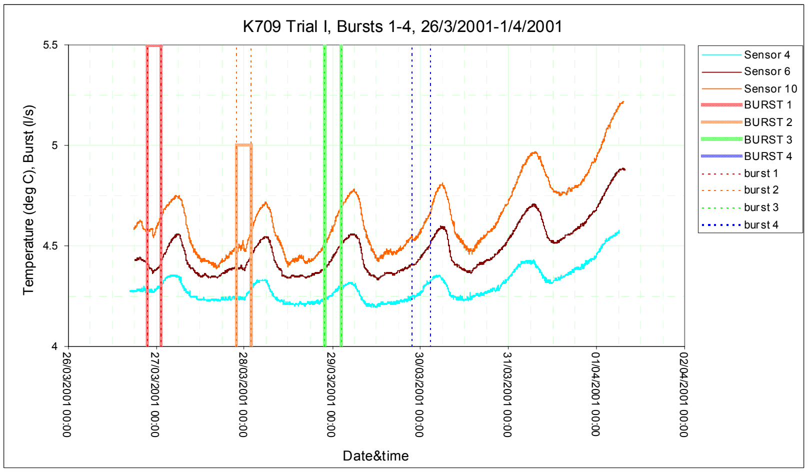

Figure 3: Recorded Temperature Data for Burst Trial I – All Bursts

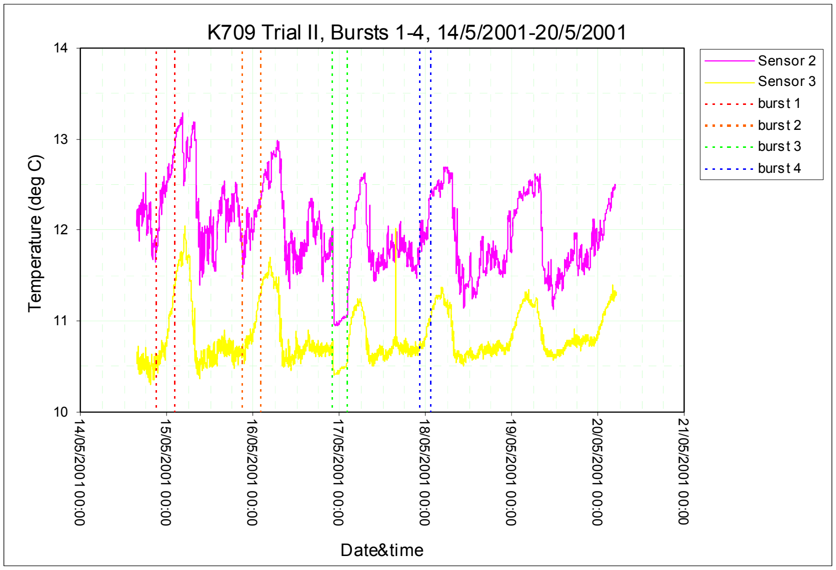

Figure 4: Recorded Temperature Data for Burst Trial I – All Bursts

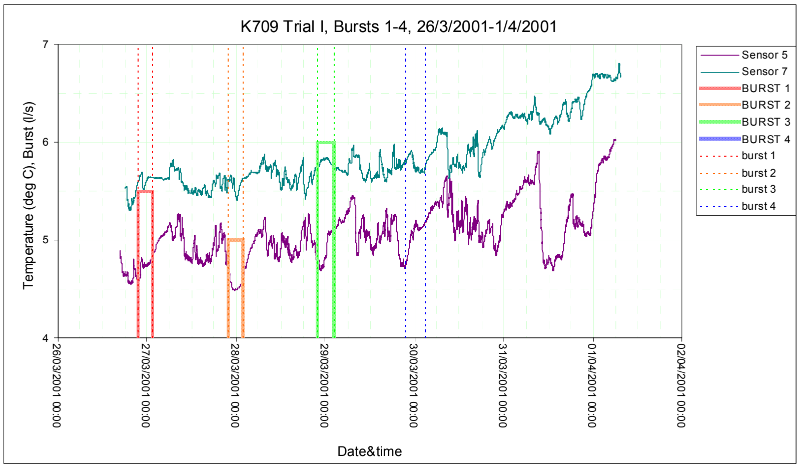

Figure 5: Recorded Temperature Data for Burst Trial I – All Bursts

The responses in this second set of experiments were similar to those recorded in the first set of experiments; the overall responses of each sensor to both experiments are shown in Table 1.

ANALYSIS OF RESULTS

The results indicated that the response of the temperature sensor was generally limited to a relatively small change, due to the difference between the water temperature in the pipes and that at the reservoir being small. The data, examined after the trials, indicated that the nearest sensor to the reservoir (sensor 1), which could best represent the reservoir temperature, failed during the burst trial, so sensor 4, which was the next one to the reservoir was used for the analysis. The network comprised a variety of pipe dimensions and materials, and it was observed from the water temperature data that the water temperatures in the pipes with the bigger internal diameters (IDs) were generally closer to the reservoir water temperature. In a burst situation, therefore, when extra water at the reservoir water temperature is brought into the network, the water temperature in a larger ID pipe is unlikely to change to the same extent as the water temperature in a smaller ID pipe. The water temperature in either size of pipe can only change to approach that of the reservoir. Sensors in the smaller pipelines can be seen from the data to have responded significantly level to the simulated bursts.

Table 1 Temperature sensor responses for burst trial I & II

Serial No.	Trial I				Trial II			
	Burst 1	Burst 2	Burst 3	Burst 4	Burst 1	Burst 2	Burst 3	Burst 4
Sensor 1								
Sensor 2			*****	*	*		*****	*
Sensor 3			*****				*****	
Sensor 4	*	*			*			*
Sensor 5	*	****	***			*		*
Sensor 6	**	*		*	***	**		
Sensor 7				*		*		
Sensor 8		*						
Sensor 9		*						
Sensor 10	**	**		***		**		

*=possible response, **=fair, ***=good, ****=very good, *****=excellent response

The data analysis started by removing the daily cycles from the data. A model day was generated for each sensor site by taking the mean at corresponding times of each day, at 1 minute intervals of water temperature data recorded over several days. The experimental data was then normalised so as to remove the daily cycle at the sensor, making the response of each temperature sensor to the simulated burst more visible. Burst 3 was created almost at the same place in both experiments, and the responses of sensors 2 and 3 were found to be “significant” (Figure 6 & 7).

Similarly Experiment 2 in Trial I used a "burst" near Sensor 5 that was picked up by Sensor 5 (Figure 8). The results are summarised as follows:

1. A 3ºC difference in temperature at the sensors (2—10) can be seen across the pipeline network at any time (Figure 2).
2. Sensor locations in pipelines that have larger IDs and that are closer to the reservoir have a lower water temperature and smaller temperature variation cycles. This can be seen at sensors 4, 6 and 10 where the pipelines are increasingly distant from the reservoir and have IDs of 250mm, 225mm and 150mm respectively (Figure 3).
3. Smaller ID pipelines have larger temperature variation cycles. This can be seen at sensor locations 7, 2, 3 and 5 where the pipeline IDs are 75mm, 90mm, 110mm and 125mm respectively (Figures 4 & 5).
4. The closer a sensor is to a burst site, the bigger the response. This can be observed in the response of sensors 2 and 3 to Experiment 3 in both trials (Figure 4).
5. A good response at Sensor 5 can be seen for Experiment 2 of Trial I. Despite the sensor being very close to the burst the response is limited due to the large ID pipeline and closeness of the site to the reservoir (Figure 5).
6. The response at Sensor 7 to all of the experiments was negligible. Although fitted into the smallest ID pipe it was situated at a long distance from every burst site (Figure 5).

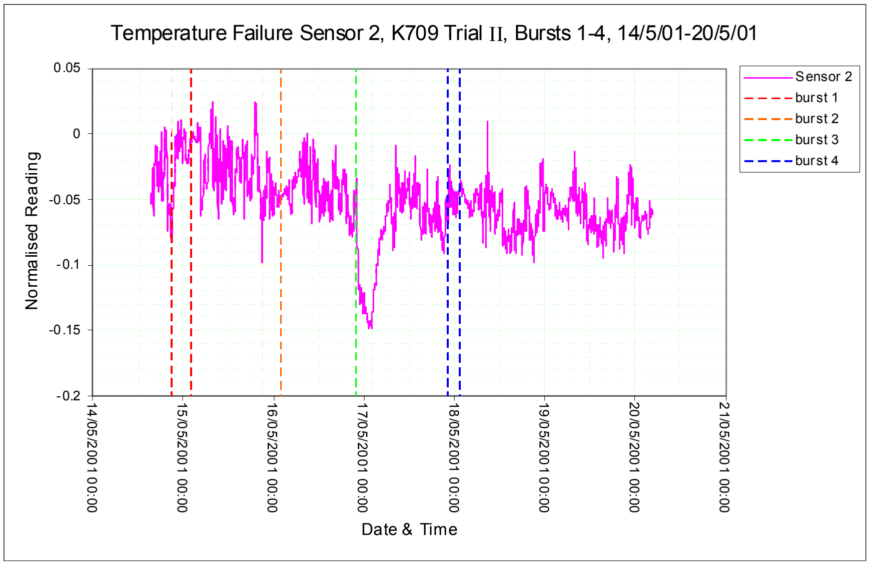

Figure 6: Normalised Temperature Data for Burst Trial II – All Bursts

NETWORK SIMULATION ANALYSIS

A simulation study was conducted using the commercially available water distribution network simulation software AQUIS for the analysis of flow, pressure and velocity at the 10 sensor locations in order to compare the effect of these parameters with the water temperature measured by the sensors during the experiments under similar conditions. One leak (20mm diameter) per 24 hours duration was created on 4 separate days and the analysis was made for every sensor location for leak vs. no leak conditions. In the analysis, each leak was independent of the others and introduced into the distribution network at the location of the actual burst simulation. Each simulation for flow, pressure and velocity was run for 24 hours duration so as to visualise the effect of a leak with the daily cycle in the system. The full AQUIS simulation for the flow velocity analysis at 10 sensor locations is shown in Figure 9. The response to each simulated leak at the 10 virtual sensor locations was found to be dependent upon:

(i) the overall position of the sensor within the DMA,
(ii) the closeness of the sensor location to the leak site and
(iii) the magnitude of the leak simulated at any particular location.

The results of the AQUIS simulation can be explained as:

1. An additive response to the leak created in any part of the distribution network was shown in the sensor locations 1 & 4, due to the unidirectional flow at these locations.
2. Sensors in the central portion (2, 3, 5, 6, & 7) gave a response dependent upon the distance of the leak from the sensor locations.
3. Sensor 10 responded to a lesser extent to all leaks created in the system, as the flow, pressure and velocity were low in this section.
4. Sensor locations 8 & 9 did not respond to any leak, as both sensors were in an isolated part of the network which is totally controlled by a pressure regulating valve (PRV).

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

These results identified leaks in close vicinity of the central section of the network. After the completion of experiments on sensors and AQUIS simulation, the outcomes of both studies were compared as follows:

1. In both the simulation study and the experiments, the sensors in the central area (2, 3, 5 & 6) responded significantly to any burst in the close vicinity.
2. Smaller diameter pipes showed a significant response (sensors 2 & 3 particularly) in both studies (Figure 4).
3. Larger diameter pipes also showed a response (sensors 4, 6 & 10) (Figure 3).
4. For burst detection, Sensor 5 was the best sensor location in the whole DMA.
5. Sensor 10 responded less significantly in both studies, as that portion of the network was isolated.
6. Sensors 8 and 9 showed negligible response to any of the investigations.

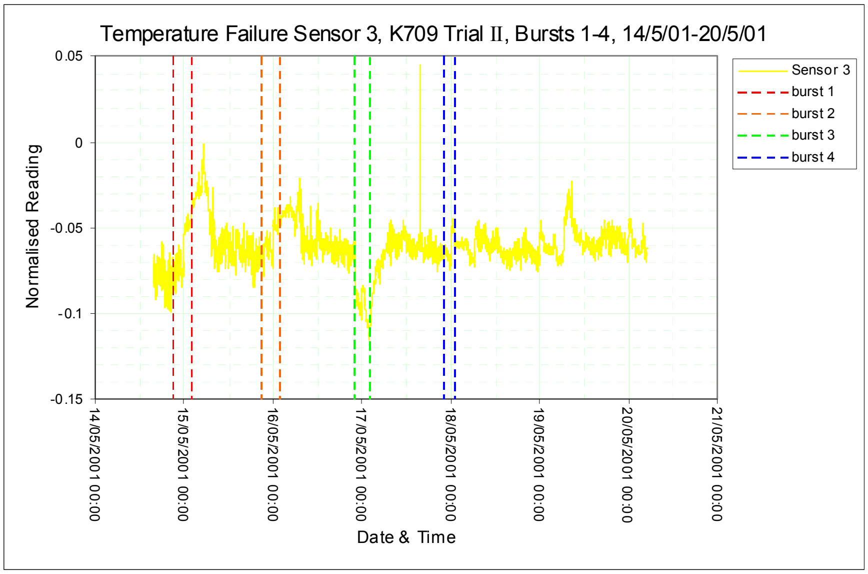

Figure 7: Normalised Temperature Data for Burst Trial II – All Bursts

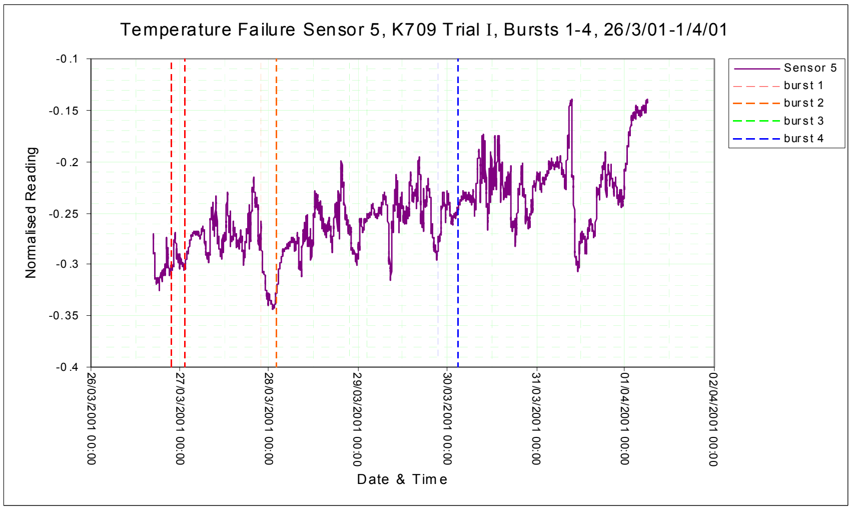

Figure 8: Normalised Temperature Data for Burst Trial I – All Bursts

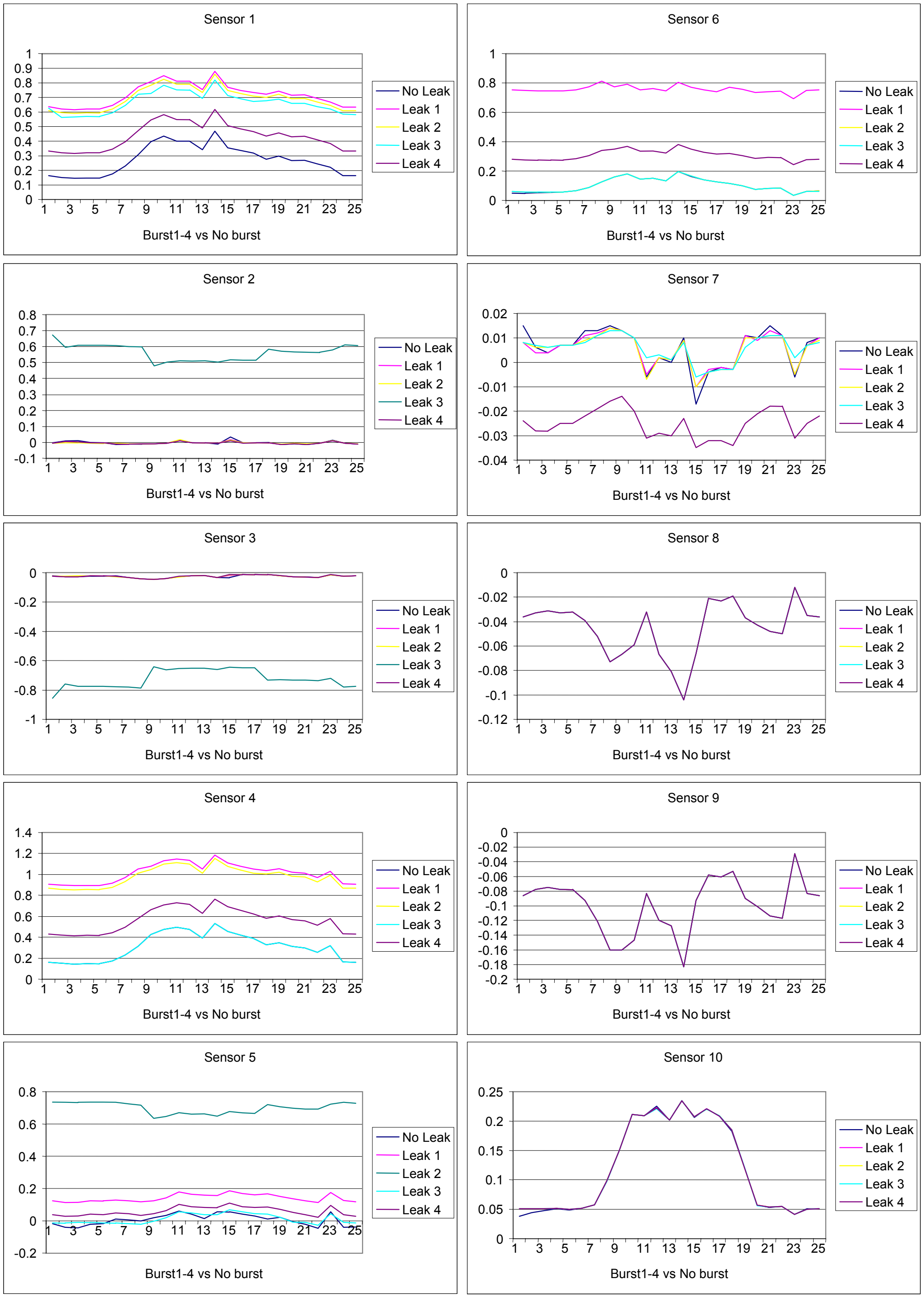

Figure 9: Aquis Velocity Simulation of Flow at 10 Temperature Sensor Locations for Leak 1-4 vs. no Leak

CONCLUSIONS

The temperature of the water in a water distribution pipeline system varies with location. In general, the water temperature increases with distance from the reservoir or input (to a DMA). When an event occurs (leak or burst), the local water temperature changes; a temperature reduction caused by increased flow of colder water into the locality. This effect is more pronounced with smaller diameter pipes.

Correlation was found between the measured temperature effects and the results from flow rate simulation. The extent of the changes in temperature was consistent with calculated changes in flow rate. Correlation with simulated bursts has been clearly demonstrated, supporting both measured and simulated results.

Low cost sensor technology in the form of temperature sensors can usefully indicate the state of "health" of a water pipeline distribution network. Low-cost sensor technology can thus contribute to a system for monitoring and leak detection in water distribution pipelines. Such technology can be deployed alongside more costly sensors to measure hydraulic parameters.

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